(2)

Report No. NADC-91041-60

IN SITU LIQUID-CRYSTAL-POLYMER FIBER REINFORCED ALUMINUM MATRIX COMPOSITE

William E. Frazier and Gilbert J. London
Air Vehicle and Crew Systems Technology Department (Code 6063)
NAVAL AIR DEVELOPMENT CENTER
Warminster, PA 18974-5000

Jorge E. Talia
Department of Mechanical Engineering
The National Institute for Aviation Research
THE WICHITA STATE UNIVERSITY
Wichita, KS 67208

1 MAY 1991

FINAL REPORT
Period Covering 1 October 1989 to 1 October 1990
Task No. 1
Project No. RS34A50

Approved for Public Release; Distribution is Unlimited

Prepared for
NAVAL AIR SYSTEMS COMMAND (AIR-51412)
Washington, DC 20361-0001

NOTICES

REPORT NUMBERING SYSTEM — The numbering of technical project reports issued by the Naval Air Development Center is arranged for specific identification purposes. Each number consists of the Center acronym, the calendar year in which the number was assigned, the sequence number of the report within the specific calendar year, and the official 2-digit correspondence code of the Command Officer or the Functional Department responsible for the report. For example: Report No. NADC-88020-60 indicates the twentieth Center report for the year 1988 and prepared by the Air Vehicle and Crew Systems Technology Department. The numerical codes are as follows:

CODE	OFFICE OR DEPARTMENT
00	Commander, Naval Air Development Center
01	Technical Director, Naval Air Development Center
05	Computer Department
10	AntiSubmarine Warfare Systems Department
20	Tactical Air Systems Department
30	Warfare Systems Analysis Department
40	Communication Navigation Technology Department
50	Mission Avionics Technology Department
60	Air Vehicle & Crew Systems Technology Department
70	Systems & Software Technology Department
80	Engineering Support Group
90	Test & Evaluation Group

PRODUCT ENDORSEMENT — The discussion or instructions concerning commercial products herein do not constitute an endorsement by the Government nor do they convey or imply the license or right to use such products.

Reviewed By: J. Walker Date: 5 June 91
Branch Head

Reviewed By: W J Smith Date: 25 June 1991
Division Head

Reviewed By: W J Smith Date: 25 June 1991
Director/Deputy Director

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release; Distribution is Unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): NADC-91041-60	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Air Vehicle and Crew Systems Technology Department; 6b OFFICE SYMBOL (If applicable): 6063	7a NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code): NAVAL AIR DEVELOPMENT CENTER, Warminster, PA 18974-5000	7b ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: NAVAL AIR SYSTEM COMMAND; 8b OFFICE SYMBOL (If applicable): AIR-51412	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code): Washington, DC 20361-0001	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO; PROJECT NO: RS34A50; TASK NO: 1; WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification)
In Situ Liquid-Crystal-Polymer Fiber Reinforced Aluminum Matrix Composites.

12 PERSONAL AUTHOR(S)
William E. Frazier[1], Gilbert J. London[1] and Jorge E. Talia[2]

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM 10/89 TO 10/90	1991 May 1	

16 SUPPLEMENTARY NOTATION
See Reverse Side

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
11	06		Polymer, fibers, LCP, composite, MMC

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

POLYMETS are a new class of hybrid materials composed of metals and polymers. The microstructures and properties of POLYMETS can be customized to meet a wide variety of design requirements. In this research, five to twenty volume percent of a thermotropic, wholly aromatic, liquid crystal polymer (Vectra B950) was mixed with -240/+325 mesh commercially pure aluminum powder and hot extruded at 300 °C. The tensile properties of these POLYMETS were evaluated and the results compared to a pure aluminum control specimen. Optical and electron microscopy were used to examine the microstructures of the extruded rods and fracture surfaces of the tensile specimens. It was observed that polymer fibrils aligned in the extrusion direction.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: Dr. William E. Frazier	22b TELEPHONE (Include Area Code): 215-441-1301; 22c OFFICE SYMBOL: 6063

DD Form 1473, JUN 86 Previous editions are obsolete SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603 UNCLASSIFIED

Block 16.

William E. Frazier[1], Gilbert J. London[1], and Jorge E. Talia[2]

1. Naval Air Development Center
   Aerospace Materials Division (Code 6063)
   Warminster, PA 18974-5000

2. Department of Mechanical Engineering
   The National Institute for Aviation Research
   The Wichita State University
   Wichita, KS 67208

CONTENTS

FIGURES

TABLES

Introduction

Recent research by Frazier, Austen, and London [1] has demonstrated the feasibility of extruding metal-polymer composites (POLYMETS) of alumium/PEEK and aluminum/Xydar. Extrusion through a high shear, 90 $^{\circ}$ die (as shown schematically in Figure 1) or a converging conical die, improves the properties of these aluminum-polymer composites. This is believed to be the result of texture development, that is, the bulk and molecular orientation of the polymer in the extrusion direction. The yield strengths of these metal-polymer composites were found to be 13 to 18 percent greater than that predicted by the rule-of-mixtures, and their specific yield strengths were found to be 14 to 21 percent greater than that of the aluminum control specimen.

The properties of polymers such as polyethylene (PE), polypropylene (PP), and polyetheretherketone (PEEK) have been substantially improved by extrusion and drawing through conical converging dies. Richardson, et al. [2] reports nearly a three fold increase in modulus for PEEK after drawing through a die reduction of 3:1 at 310 $^{\circ}$C. Such an improvement has been attributed to the molecular alignment produced by the drawing operation. Several studies indicate that thermotropic, liquid-crystal copolyesters that exhibit rigid rod-like morphologies in the melt are readily drawn into fibers [3,4,5, & 6]. Sawyer and Jaffe [3] report that fibers produced from copolyesters of 2,6 Naphthyl and 1,4 phenyl exhibit a hierarchical fibril microstructure. Fibril diameters range from 5 micron macrofibrils to 0.05 micron microfibrils depending upon local shear stresses. In another study, Isayev and Modic [7] have shown that, under certain conditions, thermotropic, liquid-crystal polymers form high modulus and high strength filaments when deformed in a flexible polymer matrix at high strain rates.

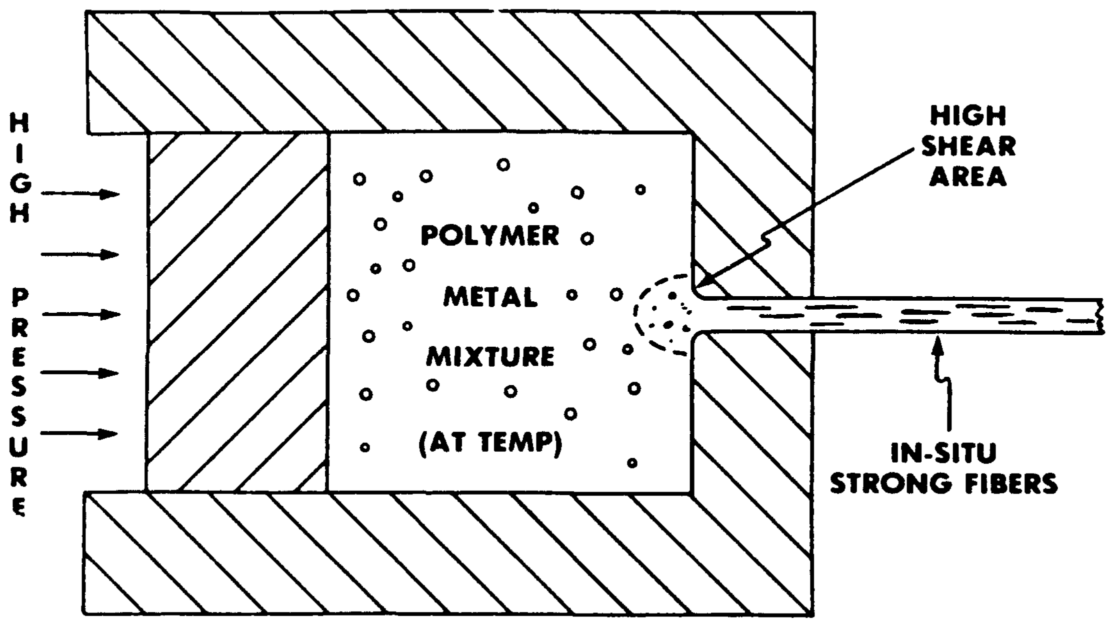


Figure 1 - The POLYMET extrusion process illustrating the formation of fibers in situ.

The purpose of this investigation was to explore the potential of producing metal matrix composites with fiber-like structures formed in situ during extrusion. The focus of this work is on the effect of extrusion ratio on the microstructure and mechanical properties of the POLYMETS.

Experimental Work

Materials Processing

The POLYMETS examined in this research were prepared from commercially pure aluminum and Vectra, a wholly aromatic, thermotropic, liquid-crystal copolyester (LCPE). The aluminum forms the matrix; the polymer is the second phase reinforcement. Processing involved extensive extrusion deformation in order to directionally align the polymeric material. In addition, a commercially pure aluminum alloy was prepared in an identical manner to the POLYMETS and used as a control specimen. The test matrix and material designations are provided in Table I.

Table I. Test Matrix .

Material	Extrusion Ratio 10.7/1	114/1	1225/1
CP Aluminum	S_Al	D_Al	N/A
Al 5 vol.% Vectra	S_V05	D_V05	T_V05
Al 10 vol.% Vectra	S_V10	D_V10	T_V10
Al 20 vol.% Vectra	S_V20	D_V20	T_V20

The processing schedule is presented in Figure 2. Vectra pellets, three to four millimeters in diameter, (Figure 3a) were comminuted and screened to -20 mesh. The metal-polymer blends were prepared by mixing -240/+325 mesh, commercially pure, aluminum powder (Figure 3b) and Vectra powder in a rotating V-cone blender for one hour. The powder blends were sealed in a fully annealed 2024 aluminum can. The canned powders were vacuum degassed at 300 ^{o}C (572 ^{o}F) for approximately one hour. The materials were then hot extruded on a 200 ton Innovare extrusion press at 300 ^{o}C (572 ^{o}F) using an extrusion die with an angle of 45^{o} and area reduction 10.7/1. The POLYMETS were evaluated after the can material was scalped. Portions of the materials were canned, vacuum degassed, and re-extruded for effective area reductions of 114/1 and 1225/1.

Microstructural Characterization

Samples were prepared for optical examination by mounting them in finely ground dially phthalate powder. The mounted specimens were hand polished on successively finer grades of abrasive paper, i.e., 220, 320, 500, and 1000 grit. Because the unalloyed aluminum matrix was extremely soft, the samples were lapped in a solution of suspended silica. Metallographic samples were observed in the unetched condition on a Nikon metallograph.

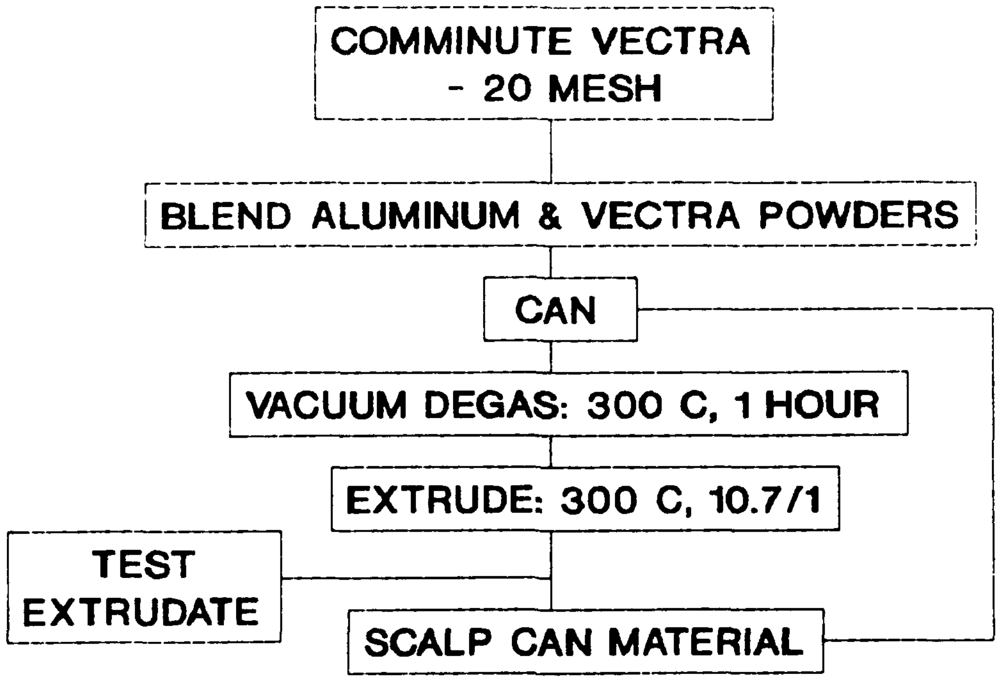


Figure 2 - POLYMET processing schedule

In order to better understand the deformation behavior of these materials, fractured tensile specimens were examined using scanning electron microscopy (SEM). The fracture surfaces of the tensile specimens were examined using an Amray scanning electron microscopy (SEM) operated at 30 kv in the secondary electron emission mode.

Mechanical Properties

Tensile tests were performed on the consolidated alloys in order to evaluate their ambient temperature response. Tensile tests were conducted in accordance with ASTM E8-81 on a instron test machine at a strain rate of 10^{-3} s^{-1}. The tensile specimens were 100 mm long and 6 mm in diameter. The reduced section was 16 mm long and 4 mm in diameter.

Experimental Results and Discussion

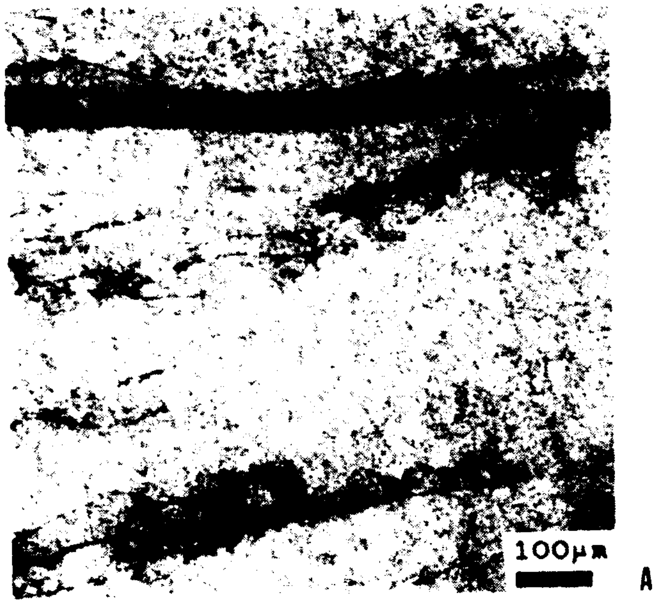
Microstructure

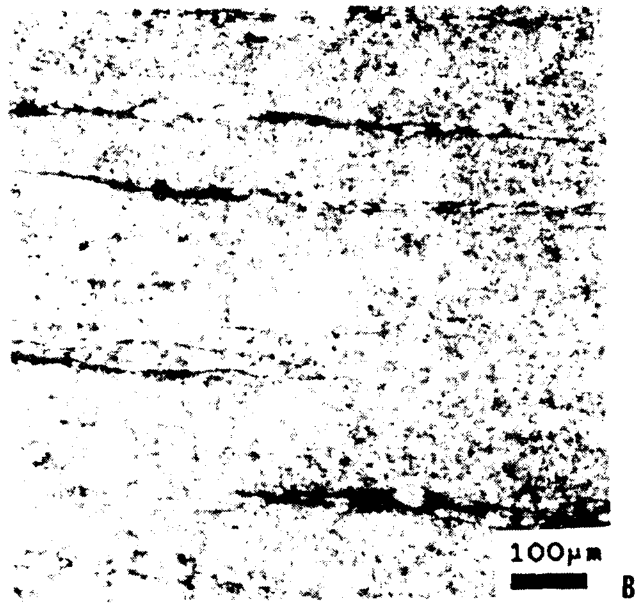
The microstructures observed by extruding the Al-5 vol.% vectra POLYMET at 10.7/1, 114/1, and 1225/1 are presented in Figure 4. The polymer phase is seen to elongate and thin in the extrusion direction. The observed breadth of the polymeric phase in POLYMETS extruded at 10.7/1 is between 20 and 50 microns, and the breadth of the POLYMETS extruded at 114/1 is less than 10 microns. The breadth of the polymer phase in POLYMETS extruded at area reductions of 1225/1 is between 0.5 and 3 microns.

A

B

Figure 3 - Starting POLYMET materials: (a) Vectra B950 pellets and (b) commercially pure -240/+325 mesh aluminum powder.





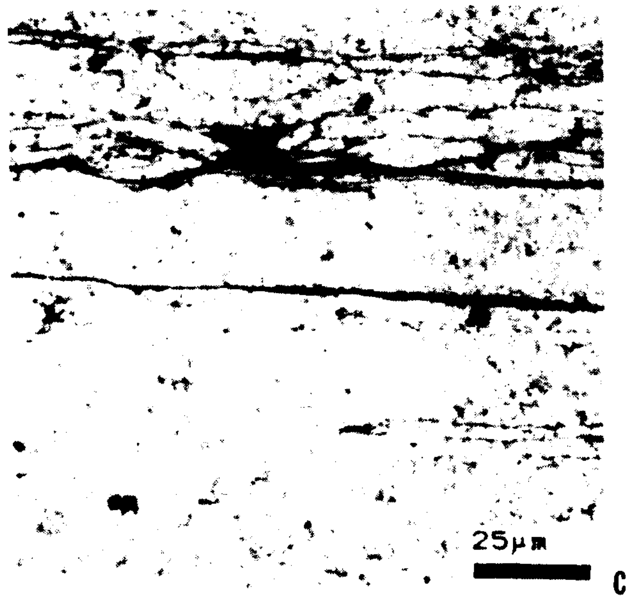


Figure 4 - Optical micrographs of Al-5 vol.% Vectra extruded at (a) 10.7/1, (b) 114/1, and (c) 1225/1.

Similar to the Al-5 vol.% Vect: ı material, the polymer phase, in POLYMETS with 10 and 20 vol.% Vectra, elongates and thins in the extrusion direction. However, the higher polymer content promotes polymer segregation and isolated aluminum powder particles often appear as "islands" in a "sea" of polymer. During extrusion, the polymer inhibits and often prevents these isolated aluminum powder particles from bonding with the matrix.

Tensile Properties

The stress-strain behavior of the POLYMETS extruded at 10.7/1 and 114/1 are reported in Figures 5 and 6, and Table II. The strength and ductility of the POLYMETS decreases with increasing polymer content. For POLYMETS extruded at 10.7/1, the yield strength decreases from 100.9 MPa to 55.9 MPa as the vol.% vectra is increased from 5% to 10%. Ductility also decreases; tensile elongation declines from 1.6% to 1.2%.

Table II Tensile Properties of the Aluminum-Vectra POLYMETS.

MATERIAL	YS, MPa	UTS, MPA	% ELONG.
Ext. Ratio: 10.7/1			
S_Al	115.1	136	18.3
S_V05	100.9	104	1.6
S_V10	55.9	57.7	1.2
S_V20	11.2	11.2	0.5
Ext. Ratio: 114/1			
D_Al	83.0	138	27
D_V05	83.9	144	7.5
D_V10	53.9	72.5	1.6
D_V20	10.6	14.3	0.8

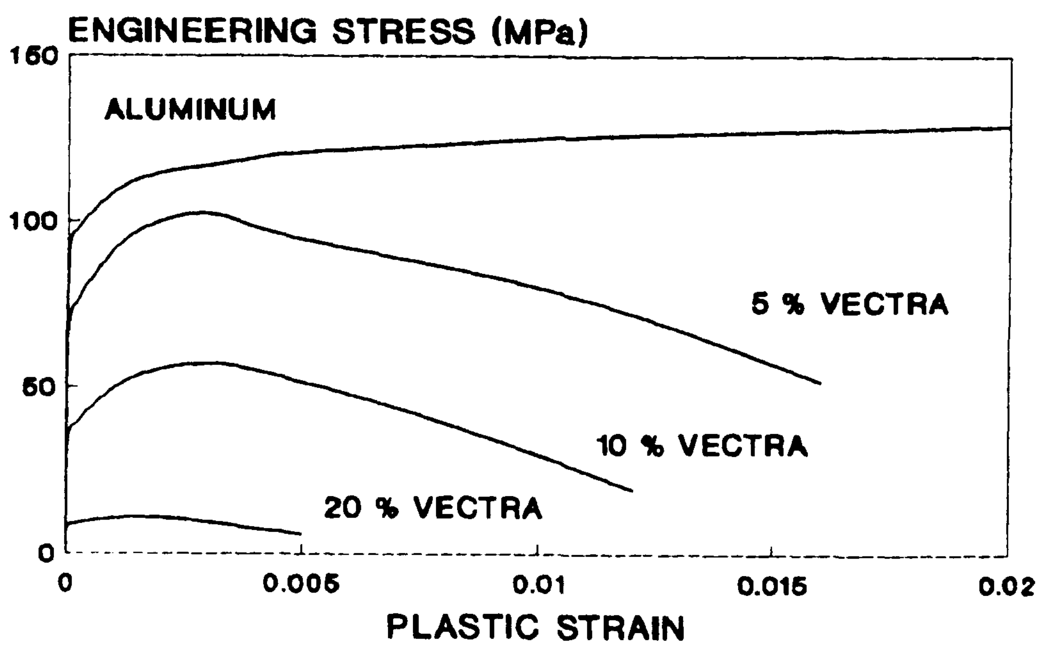


Figure 5 - Tensile stress-strain behavior of POLYMETS extruded at 10.7/1.

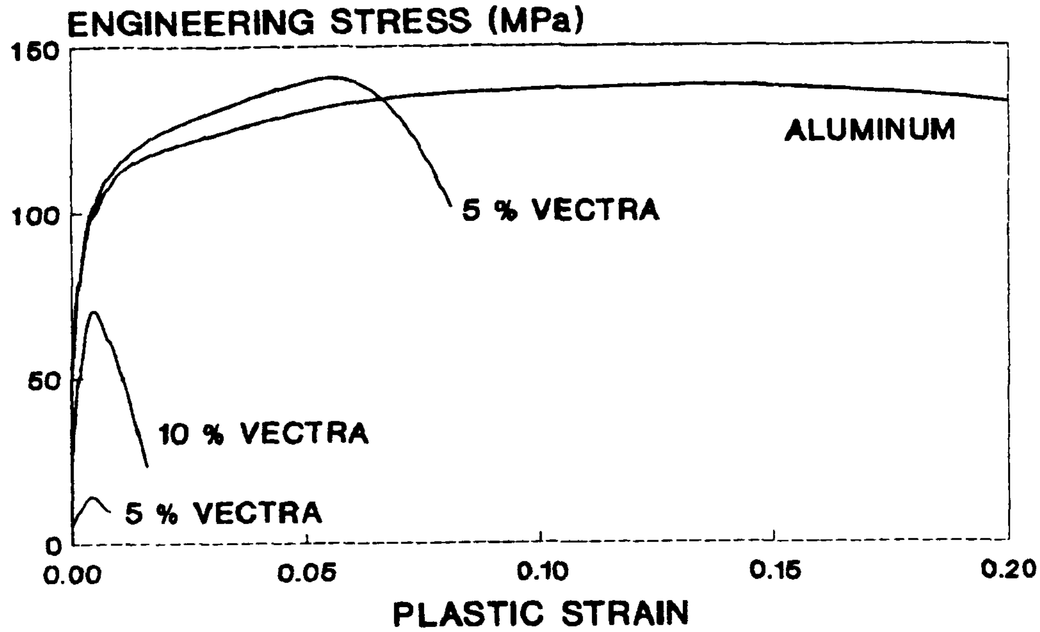


Figure 6 - Tensile stress-strain behavior of POLYMETS extruded at 114/1.

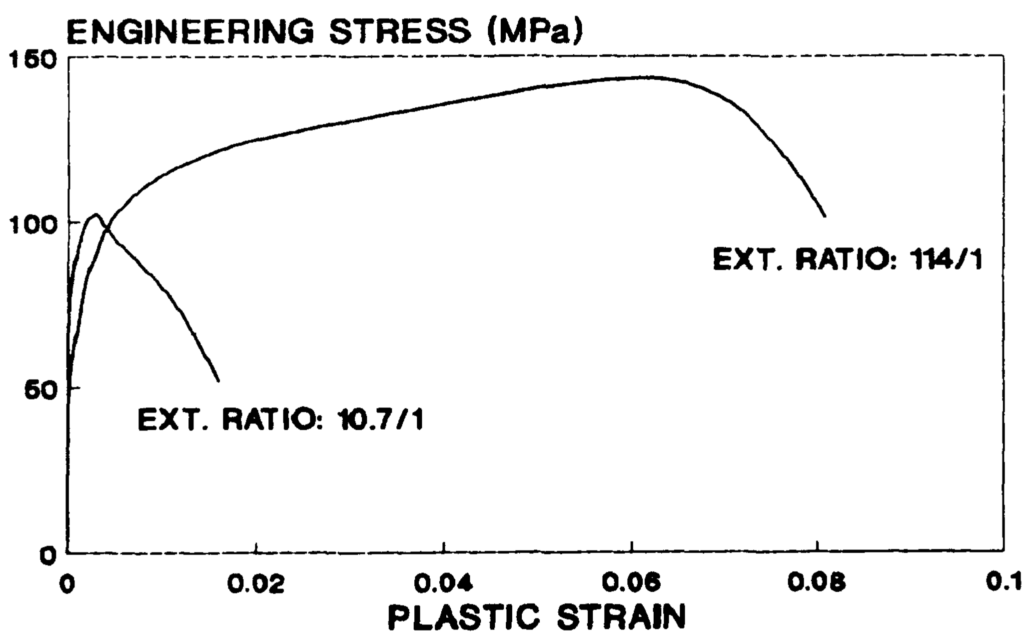


Figure 7 - Tensile stress-strain behavior of Al-5 vol.% Vectra extruded at 10.7/1 and 114/1.

The properties of the POLYMETS are affected by the extrusion ratio: high extrusion ratios decreased yield strength, increased ultimate tensile strength, and improved ductility. The yield strength of aluminum extruded at 10.7/1 and 114/1 decreased from 115.7 MPa to 83.0 MPa. Ductility of the aluminum increased from 18.3% to 27.0%; however, the ultimate tensile strength of the aluminum remained virtually unchanged, i.e., between 136 and 138 MPa.

The stress-strain curves for Al-5 vol.% Vectra extruded at 10.7/1 and 114/1 are shown in Figure 7. The yield strength of aluminum 5% Vectra decreased from 100.9 MPa to 83.9 MPa when extruded at reduction ratios of 10.7/1 and 114/1, respectively; however, the ultimate tensile strength increased from 104 MPa to 144 MPa. The elongation of aluminum 5% Vectra increased significantly with extrusion ratio from 1.6 to 7.5.

An approximation of the energy required to cause tensile failure was obtained by measuring the area under the stress-strain curve. These data are presented in Table III. The energy expended to cause tensile failure of a POLYMETS is affected by the extrusion ratio: high extrusion ratios increase expended energy. The energy absorbed by aluminum 5% Vectra extruded at 10.7/1 and 114/1 increased from 1.3 mJ/mm^3 to 10 mJ/mm^3, i.e., nearly 670%.

Table III The Approximate Energy Expended During Tensile Examination.

MATERIAL	ENERGY (mJ/mm^3)	
	EXTRUSION RATIO	
	10.7/1	114/1
Aluminum	20	35
Al-5% Vectra	1.3	10
Al-10% Vectra	0.5	0.94
Al-20% Vectra	0.04	0.11

The yield strengths of the POLYMETS decreased with increased extrusion ratio. Interestingly, however, there was also a concomitant decrease in the yield strength of the aluminum control specimen. Further microstructural analysis is required in order to unambiguously identify the cause of this decrease. Although among the possible causes are processes involving matrix recovery, recrystallization, and grain growth.

In order to more accurately assess the effect of extrusion ratio on POLYMET yield strength, the decrease in matrix yield strength (as observed in the aluminum control sample) must be taken into account. The normalized yield strengths of the POLYMETS (based on the properties of the aluminum control samples) are presented in Table IV.

Table IV. Normalized Yield Strength.

MATERIAL	YIELD STRENGTH (MPa)	
	EXTRUSION RATIO	
	10.7/1	114/1
Aluminum	115.1	115.1
Al-5% Vectra	100.9	116.3
Al-10% Vectra	55.9	74.7
Al-20% Vectra	11.2	14.7

The normalized yield strengths of the POLYMETS increase with extrusion ratio. The average normalized yield strength of the POLYMETS extruded at 114/1 is 26.7% greater than those extruded at 10.7/1. The normalized yield strength of the aluminum-5 vol.% Vectra increased 15.3%, i.e., from 100.9 MPa to 116.3 MPa. By inference, the increase in normalized yield strengths of the POLYMETS is attributable to morphological and crystallographic changes in the polymeric phase.

Fracture Behavior

Representative fractographs of POLYMETS extruded at 114/1 are presented in Figure 8. Polymer films, typically 0.5 microns thick and over 10 microns wide, are clearly visible. The polymer films appear to emanate from grain boundaries or prior particle boundaries. This type of fracture morphology may indicate poor matrix cohesion and result in lower ductility and reduced transverse strength. There was insufficient 1225/1 extruded material produced to determine tensile properties, but the very fine fibrils shown in the microstructure of the 5% Vectra material appear encouraging.

Fractographs of Al-5 vol.% Vectra clearly show fibrils emanating from matrix dimples, Figure 9a & 9b. The fibrils are approximately 1.5 microns in diameter. The dimple size and spacing is similar to that of the aluminum control specimen, Figure 9c.

Conclusions

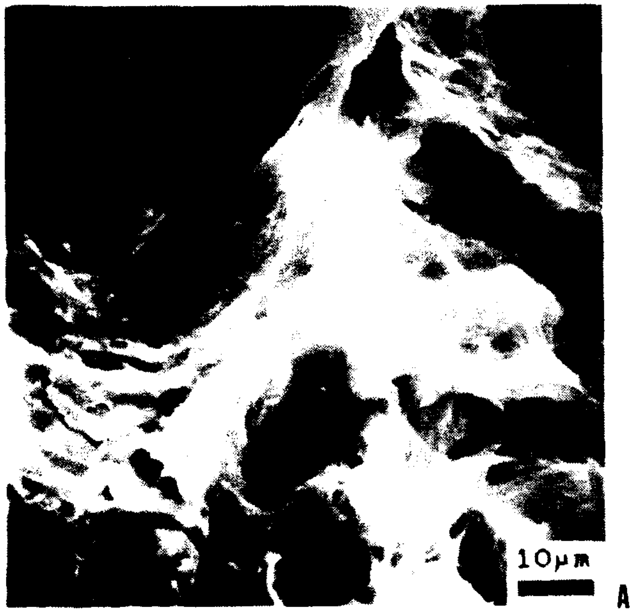
1. In situ fibril and film formation was observed and was the result of extrusion processing.

2. The ultimate tensile strength and ductility of aluminum/Vectra POLYMETS is improved by increasing the extrusion ratio from 10.7/1 to 114/1.

3. The yield strengths of the POLYMETS declined by increasing the extrusion ratio; however, the normalized yield strengths of the POLYMETS increased an average of 26.7%.

4. Increases in the ultimate tensile strengths and normalized yield strengths of the POLYMETS with extrusion ratio are attributable to polymer fibril and film formation.

5. The energy required to produce tensile failure is significantly enhanced by increasing the extrusion ratio from 10.7/1 to 114/1.



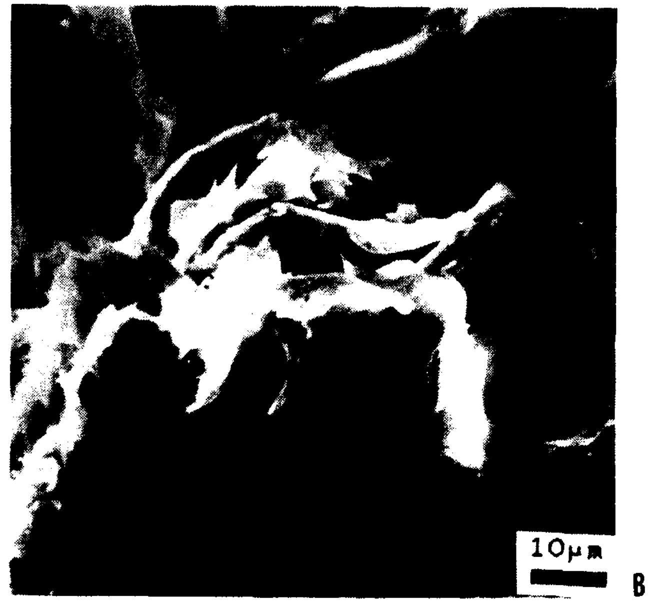


Figure 8 - SEM fractographs of POLYMETS extruded at 114/1: (a) Al-5 vol.% Vectra, (b) Al-10 vol.% Vectra, and (c) Al-20 vol.% Vectra.

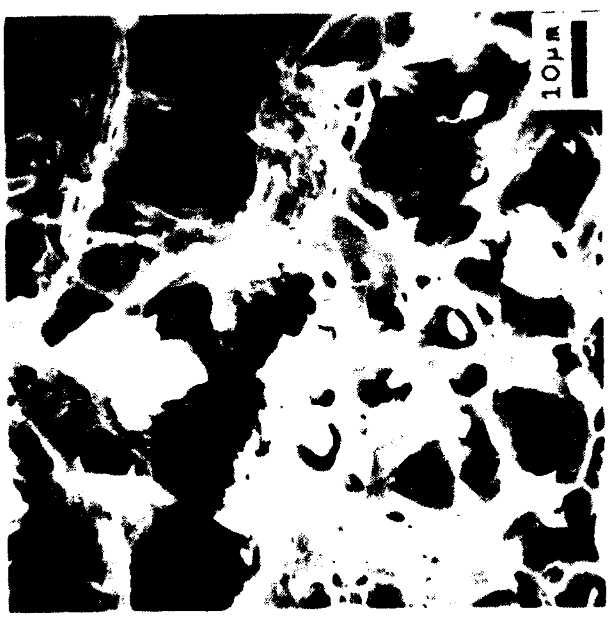


Figure 9 - SEM fractograph of Al-5 vol.% Vectra extruded at 1225/1: (a) multiple polymer fibrils, (b) a single fibril in a matrix dimple, and (c) the aluminum control specimen extruded at 10.7/1.

References

1. W.E. Frazier, G.J. London, and A.R. Austen, "Microstructure and Properties of Extruded P/M Aluminum Polymer Blends," ed. R. Bhagat et al., Metal and Ceramic Matrix Composites: Processing, Modeling & Mechanical Behavior, (Warrendale, PA: TMS, 1990), 597-604.

2. A. Richardson, F. Amia, D. R. Rueda, I. M. Ward, and F. J. Balta Calleja, "The Production and Properties of Poly(arylether ketone) (PEEK) Rods Oriented by Drawing Through a Conical Die," Polymer Engineering and Science, 25(6)(1985), 355-361.

3. L.C. Sawyer and M. Jaffe, "The Structure of Thermotropic Copolyester," Journal of Material Science, 21(1986), 1897-1913.

4. F.C. Jaarsma, J.C. Chen, and D.O. Conley, "A New Chemically Resistant Liquid Crystal Polymer," Proceedings of the Plastics Symposium "Managing Corrosion with Plastics," Celanese Corp., 1985.

5. G.D. Butzbach, J.H. Wendorff, and H.J. Zimmermann, "Structure formation in rigid chain polymer," Makromol. Chem., Rapid Commun., 6(1985), 821-823.

6. A.E. Zachariades and J.A. Logan, "The Preparation of Oriented Morphologies of the Thermotropic Aromatic Copolyester of Poly(ehtylene Terephalate) and 80 Mole Percent p-Acetoxybenzoic Acid," Polymer Engineering and Science, 23(15)(1983), 797-802.

7. A.I. Isayev and M. Modic, "Self-Reinforced Melt Processible Polymer Composites: Extrusion, Compression, and Injection Molding," Polymer Composites, 8(3)(1987), 158-175.

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
University of California Dept. of Mechanical Engineering Irvine, CA 92717 E. J. Lavernia	1
University of California Dept. of Materials Science Berkeley, CA 94720 J. Morris, Jr., R. O. Richie	2
University of California Santa Barbara, CA 93106 C.G. Levi	1
University of Michigan H.H. Dow Building Ann Arbor, MI 48109-2136 A. Ghosh	1
University of Pennsylvania *School of Engineering* and Applied Science 109 Town Building Philadelphia, PA 19104-6391 D. Pope	1
University of Virginia Light Metals Center Charlottesville, VA 22901 J. Wawner, J. Wert, H.N.G. Wadley, E.A. Starke, Jr.	4
USAF Systems Command WPAFB, OH 45331	1
Wayne State University Detroit, MI 48202 J. Benci	1

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
Oak Ridge National Laboratory P.O. Box 2008 Oak Ridge, TN 37831-6077 R.H. Cooper	1
Office of Naval Research 800 Quincy St. Arlington, VA 22217-5000 S. Fishman, Code 12 G. Yoder, Code 11 J. Kelly, Code OCNR-225	3
Pratt and Whitney P.O. Box 109600 West Palm Beach, FL 33410-9600 B.H. Walker, R. Anderson	2
Reynolds Metals Co. Fourth and Canal St. P.O. Box 27003 Richmond, VA 23261-7003 A. Cho, D. Thompson	2
Rockwell International, Science Center 1049 Camino Dos Rios P.O. Box 1085 Thousand Oaks, CA 91360	1
Sandia National Laboratory Albuquerque, NM 87185 Div. 1822 and 1832	2
Textron 2 Industrial Ave. Lowell, MA 01851 M. Mittnick	1
The Wichita State University Wichita, KS 67208 J.E. Talia	1
TRW, Inc. 23555 Euclid Ave. Cleveland, OH 44117	10
U.S. Army Air Mobility R&D Laboratory Fort Eustis, VA 23064 SAVDL-EU-SS	1

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
Naval Surface Warfare Center Silver Spring, MD 20903-5000 D. Divecha	1
NAVAVNDEP, MCAS Cherry Point, CA Code 340	1
NAVAVNDEP, NAS Alameda, CA Code 340	1
NAVAVNDEP, NAS Jacksonville, FL Code 340	1
NAVAVNDEP, NAS Norfolk, VA Code 340	1
NAVAVNDEP, NAS North Island, CA Code 340	1
NAVAVNDEP, NAS Pensacola, FL Code 340	1
NAVAVNSAFECEN, NAS Norfolk, VA	1
NAVSEASYSCOM Washington, DC 20362	1
NAVSHIPRANDCEN Annapolis, MD 21402	1
NAVSHIPRANDCEN Bethseda, MD 20034	1
Northrop, Aircraft Division One Northrop Ave. Hawthorne, CA 90250 S.P. Agrawal and G.R. Chanani	2

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
NAVAIRSYSCOM Washington, DC 20361 J. Collins Air-5304	1
NAVAIRTESCEN Patuxent River, MD	1
Naval Air Engineering Center Lakehurst, NJ 08733-5100 Richard Celin (AV624-2173) Regina Jablonski (AV624-2174) Greg Fisher (SESD) (AV624-1179)	3
Naval Air Propulsion Test Center P.O. Box 7176 Trenton, NJ 08628-0176 Frank Warvolis (PE34) Andy Culbertson R. Mahortor	3
Naval Air System Command Washington, DC 20361-5140 Richard A. Retta (AIR-51412) Jennifer Jarrett (AIR-51412J) Lew Sloter (AIR-931A)	3
Naval Industrial Resources Support Activity Bldg. 75-2 Naval Base Philadelphia, PA 19112-5078 Leo Plonsky (NAVIRSA-203) David Fabry (NAVIRSA-204)	2
Naval Post Graduate School Mechanical Engineering Department Monterey, CA 93943 T. McNelly	1
Naval Research Laboratory Washington, DC 20375 Code 6120, Code 6306	2
Naval Ship Engineering Center Washington, DC 20360 Code 6101E	1
Naval Surface Warfare Center Dahlgren, VA 22448-5000	1

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
MCIC, Battelle Memorial Institute Columbus, OH	1
Metal Working News 201 King of Prussia Rd. Radnor, PA 19089 R.R. Irving	1
Metal Working Technology Inc. 1450 Scalp Avenue Johnstown, PA 15904 W.L. Otto	1
Metcut-Materials Research Group P.O. Box 33511 Wright Patterson AFB, OH 45433 Y.W. Kim	1
Michigan Technological University Houghton, MI 49931 M. McKimpson	1
NASA Headquarters 600 Independence Ave. Washington, DC 20546 N. Mayer, S. Vennesi	2
NASA Langley Research Center Hampton, VA 23365 L. Blackburn, J. Wagner, D. Roysten, D. Tenney	4
National Bureau of Standards Gaithersburg, MD 20899 R. Shaffer, J. R. Manning	2
National Science Foundation Office of Science and Technology Centers Division 1800 G. Street Washington, DC 20550	1
NAVAIRDEVCEN Warminster, PA 18974-5000 Library, Code 8131 (2 Copies) W.E. Frazier, Code 6063 (15 Copies) Gil London, Code 606 (10 Copies)	27

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
Kaiser Aluminum P.O. Box 877 Pleasonton, CA 94566 K. Brown	1
Kaiser Aluminum Ravenswood Works Ravenwood, WV 26164 J.M. Hunter	1
Lockheed California Co. Burbank, CA 91520-7631 D. J. Chellman, D. Yaney	2
Lockheed Missiles and Space Co. Metlluefy Swpr. 93-10/204 3251 Hanover St. Palo Alto, CA 94304 R. Lewis and J. Wadworth	2
Marko Materials Inc. 144 Rangeway Rd. N. Billerica, MA 01862 R. Ray	1
Martin Marietta Laboratories 1450 South Rolling Rd. Baltimore, MD 21227-3898 J. Venables, K.S. Kumar	2
Martin Marietta, Michoud Division P.O. Box 29304 New Orleans, LA 70189 J. Hackett	1
Massachusetts Institute of Technology 77 Massachusetts Ave. Cambridge, MA 20139 J. Cornie	1
Material Science Corporation 1777 Walton Rd. Blue Bell, PA 19422	1
McDonnell Aircraft Co. Box 516 Saint Louis, MO 63166 K.K. Sankaran	1

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
Garrett Auxiliary Power Division 111 South 34th St. Phoenix, AZ 85010	1
Garrett Auxiliary Power Division 2739 East Washington Street P.O. Box 5227 Phoenix, AZ 85010 Carolyn McCormick	1
General Electric Co. Valley Forge Space Center Philadelphia, PA 19101	1
Grumman Aerospace Corp Bethpage, NY 11714 P.N. Adler	1
Howmet Corp. 1500 South Warner St. Whitall, MI 49461-1895 B. London	1
Idaho National Engineering Laboratory P.O. Box 1625 Idaho Falls, ID 83415 J.R. Knibloe	1
Inco Alloys International P.O. Box 1958 Huntington, WV 25720 J. deBarbadillo	1
Industrial Materials Technology P.O. Box 565 155 River St. Andover, MA 01810 R. Widmer	1
Innovare Inc. Airport Road, Commonwealth Park 7277 Park Drive Bath, PA 18014 A.R. Austin	1

DISTRIBUTION LIST (Continued)
Report No. NADC-91041-60

	No. of Copies
British Alcan Aluminum Ltd. Alcan International Southam Rd. Bambury, Orfordshire OX 167SP, United Kingdom R. Grines	1
Brookhaven National Laboratory Department of Applied Science/PSD Building 526 Upton, NY 11973	1
Center for Naval Analyses 4401 Front Ave P.O. Box 16268 Alexandria, VA 22302-0268	1
Clemson University Dept. of Mechanical Engineering Riggs Hall Clemson, SC 29634-0921 H.J. Rack	1
DARPA 1400 Wilson Blvd. Arlington, VA 22209 W. Barker, B. Wilcox	2
Defense Technical Information Center Bldg. # 5, Cameron Station Alexandria, VA 22314 (Attn. Administrator)	2
Department of Energy 100 Independence Ave. SW Washington, DC 20585 Code CE142	1
Drexel University Dept. of Materials Engineering 32nd and Chestnut St. Philadelphia, PA 19104 M.J. Koczak	1
E.I. DuPont De Nemours & Co. Government Program Development Chestnut Run Plaza P.O. Box 80702 Wilmington, DE 19880-0702	1

DISTRIBUTION LIST
Report No. NADC-91041-60

	No. of Copies
Air Force Wright Aeronautical Lab. Wright Patterson AFB, OH 45433 W. Griffith (MLTM), J. Kleek (WL/MLLM), and R.L. Kennard (MTM)	3
Alcan Rolled Products Co. 100 Erieview Plaza Cleveland, OH 44114	1
ALCOA 1501 Alcoa Building Pittsburgh, PA 15219 F.R. Billman, R. Bucci and G. J. Hildeman	3
ALCOA 1615 M. Street, N.W. Suite 500 Washington, DC 20036 P. Patrick	1
Allied-Signal Corp. P.O. Box 1021R Morristown, NJ 07960 S.K. Das and P. Gilman	2
Army Materials Technology Laboratory Watertown, MA	1
Avco Corp Applied Technology Division Lowell, MA 01851	1
Battelle Memorial Institute Columbus Laboratories 505 King Ave. Columbus, OH 43201	1
Boeing Commercial Airplane Seattle, WA W. Quist	1
Boeing Corp. Aerospace Division P.O. Box 3707 Seattle, WA 98124	1